INJURY ANALYSIS OF LAMINATED AND TEMPERED SIDE GLAZING

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ABSTRACT

The injury characteristics of tempered and laminated side glazing during collisions are analyzed. This study is based upon a comprehensive literature review, fundamental design analysis, and the results of numerous statistical studies with particular emphasis on the injury rates associated with the tempered and HPR laminated windscreens that were used concurrently in Europe in the late 1960s and 1970s. Comparative aspects of laceration, ejection, impact, eye injury, and entrapment are detailed. It is shown that the occupant is most seriously threatened by partial or complete ejection which can be effectively mitigated by laminated glazing. It is also shown that the most common glazing-related injury is laceration, the incidence of which is also reduced by laminated glazing. Injury statistics conclusively demonstrate that for each injury mechanism studied, laminated side glazing offers superior occupant protection. The relative merits of the two glazing materials are discussed from the cost, security, and comfort/convenience perspectives. The results of testing of currently marketed side glazing technology are also presented. The study is limited by the disproportionate use of tempered side glazing in vehicles on the roadway at the time of writing, and that instances of laminated side glazing preventing ejection related serious injuries are not fully reported. New contributions include the comprehensive nature of the study, testing, and analysis.

INTRODUCTION

Automobile side glazing is generally composed of 4 to 5 mm thick sheets of either tempered safety glass (TSG) or laminated safety glass (LSG). It usually demonstrates simple (single axis) or complex (multiple axes) curvature. The majority of passenger vehicles on the roadway today come equipped with tempered side glass, but recently laminated side glass has increasingly been used for its safety and convenience benefits [21].

The American regulation governing automobile glazing is found in 49 CFR Ch. V, 571.205; *Glazing Materials* [1], which indicates that the purposes of the standard are to:

1. "Reduce injuries resulting from impact to glazing surfaces
2. "Ensure a necessary degree of transparency in motor vehicle windows for driver visibility
3. "Minimize the possibility of occupants being thrown through the vehicle windows in collisions."

The federal regulation incorporates by reference a non-governmental standard, ANSI/SAE Z26.1, last revised in 1996 [5], which provides for material performance. Neither the FMVSS 205 nor the ANSI Z26.1 governs the overall safety performance of the glazing system.

The rise in popularity of sport utility vehicles (SUVs) has brought about serious occupant safety issues. With their relatively high center of gravity and narrow track width, these vehicles roll over much more easily than do sedans. Thus, ejections through window openings have also risen. Even with a significant rise in national seat belt usage, the fatal ejection rate has not proportionately diminished [39]. The National Highway Traffic Safety Administration (NHTSA) has recently investigated the requirement for occupant retention side glazing within automobiles in positions other than the windshield and ultimately decided against mandating this technology [15;39;40;42;43]. Within their analysis, NHTSA did not look at injuries such as laceration, entrapment, and eye trauma. This present research analyzes previous NHTSA work, compares injury mechanisms not investigated by NHTSA within their advanced glazing work, and presents the results of new testing. Statistical analyses focus on 1999, the last year for which data was available at the time of making the decision not to implement occupant retention side glazing across the US fleet.

LAMINATED GLASS

Laminated glass is the original *safety glazing material*. Automotive "safety glazing material" was first defined in 1938 by the American National Standards Association, which wrote, "Specifications and methods for safety glazing material (glazing material designed to promote safety and reduce or minimize the likelihood of personal injury from flying glass material when the glazing is broken) as used for windshields, windows, and partitions of land and marine vehicles and aircraft (emphasis added) [4]. This definition was subsequently altered, and the most recent revision defines "safety glazing materials as, "A product consisting of organic and/or inorganic materials so constructed or treated to reduce, in comparison with annealed sheet, plate, or float glass, the likelihood of injury to persons as a result of contact with these safety glazing materials when used in a vehicle, whether they may be broken or unbroken, and for which special requirements regarding visibility, strength and abrasion resistance are set-forth" [5].

Factory automotive laminated glass is almost universally of "trilaminate" construction featuring two plies of solar-tinted soda-lime glass sandwiching a sheet of polyvinyl butyral (PVB) that provides the impact toughness that the glass cannot. In the early 1960s, the formulation of laminated automotive glazing (principally for the windshield) was fundamentally changed for the US market to improve its safety properties [3]. The PVB interlayer thickness was doubled to 0.030" (0.76 mm), and controlled adhesion of the plies replaced maximum adhesion. Impact testing of HPR (High Penetration Resistant) laminate shows that full penetration with a 10 kg (22 lb) headform are uniformly high, e.g. 44 kph (28 mph) [49], and 48 kph (30 mph) [47]. This design requires approximately three times the kinetic energy for a blunt impactor to penetrate compared to a tempered lite [14].

Besides the safety advantages that are described herein, laminated glass demonstrates numerous ancillary advantages [11]. These include reduced ultraviolet transmission and associated fabric fade, noise attenuation, security (intrusion resistance), higher optical quality, superior visibility when broken, replacement ease, and infra-red load reduction with proper interlayer coating. A trade group, the *Enhanced Protective Glass Automotive Association* (EPGAA) [21] promotes the usage of LSG for its desirable safety, comfort and convenience properties.

TEMPERED GLASS

Tempered glass is the dominant glazing for automotive side lites, and has been since the early 1960s when it almost completely displaced laminated glass in these positions for economic reasons [56; 57]. The American Society for Testing and materials (ASTM) standard C1048-04 [6] specifies two basic levels of surface compression as a result of thermal treatment, types FT and HS. Type FT (fully tempered) generally has a minimum surface compression of at least 69 MPa (10,000 psi) or an edge compression of at least 67 MPa (9,700 psi). Fully tempered glass is generally considered to be four times as strong as annealed glass. Moveable monolithic side window glazing is always fully tempered glass. Type HS (heat strengthened) glass has a surface compression of 24-52 MPa (3,500-7,500 psi). Heat strengthened glass is approximately twice as strong as annealed glass, and has similar fracture characteristics. Most laminated side glazing in fixed window positions retains at least some heat strengthening as consequence of the forming process (that is, it is not annealed back to a stress free state after bending).

When properly constructed, the majority of fragments created during controlled fracture of tempered glass are relatively small and blocky. The pertinent federal standard, Federal Motor Vehicle Safety Standard (FMVSS) 205, *Glazing Materials* [1], requires that, post fracture, no piece away from the periphery or crack initiation site remains uncracked or has a weight exceeding 4.25 g (0.15 oz). However, uneven tempering, bending, or twisting of the lite prior to fracture can produce splines, which are fragments with large aspect ratios. If the crack produced by the tensile separation within the glass during the fracturing process does not extend to the surface, then large, internally cracked fragments remain, and are more potentially injurious than are blocky fragments.

The principal advantages of tempered glass are its reduced cost compared to laminated and its strength in compression and bending. Its strength provides lower scrap rates in production and increased blunt impact and shock performance. Further, its properties are temperature independent. It can be thinner and lighter than laminated side glass, and does provide some modest level of occupant ejection mitigation. Unlike HPR laminated glass, tempered glass cannot be used within the vehicle without restriction; tempered glass may not be used within the windshield, either alone or as one or more plies of the laminated construction.

GLAZING-RELATED INJURY STATISTICS FOR MAJOR ACCIDENTS

According to the NHTSA publication, "1999 Traffic Safety Facts [41] for the year 1999, there were 6,279,000 accidents recorded, of which 2,990,000 were towaway [17] and 277,000 of those towaway accidents involved rollover [41]. Figures 1 and 2 provide side-glazing related serious and non-serious injury estimates for towaway accidents based upon a variety of sources detailed herein. There were approximately 227,500 injuries due to flying tempered glass fragments, making this the dominant injury mode [17]. Flying tempered glass fragments cause almost exclusively non-serious injuries, with only one serious chest injury recorded within the 1999 NASS-CDS database. The "head/neck impact" category indicating ~41,300 non-serious and 740 serious injuries refers to non-lacerative contact injuries (i.e., concussion, contusion, dislocation, fracture, sprain and strain). For side glazing, the lacerative injuries were estimated to be 20,000, all of which were non-serious [17].

Side glazing related serious injuries and deaths are totally dominated by ejection, with approximately 13,100 instances in 1999 coupled with an additional ~18,800 ejection-related minor injuries [42]. The national estimate of glazing-related ocular injuries gives 2,030 occurrences. All of these were coded as minor (non-serious), as almost all eye injuries including total blindness are considered to not be life-threatening [17]. By using historical data [28;17], instances of permanent vision degradation from glazing (including windshields) can be estimated at approximately 520 for 1999. The estimate done for this research of true instances of glazing-related entrapment (not injury) that is shown in Figure 1 is 600, based upon the number of towaway accidents recorded for 1999 and historic data [17;12]; note that entrapment does not necessarily indicate injury. The statistics cited indicate that, excluding ejection, 99.5% of side glazing related injuries are not serious.

By comparison, HPR windshields yielded 99,015 total laceration injuries in 1999, of which only 202 were serious or fatal. This represents 0.2% of interactions [17]. The incidence of windshield ejection was approximately 4,420 averaged over 1995-1999 [40] using fatalities as adjusted to the 1999 FARS. Approximately 8.6% of glazing ejections are through the windshield, while frontal collisions represent well over 50% of collisions [41].

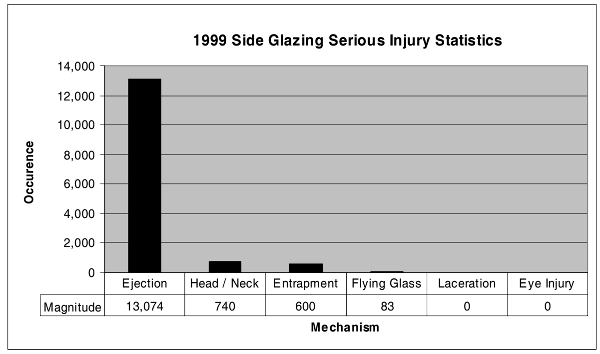

Figure 1: Estimates of side-glazing related serious injury occurrence by type.

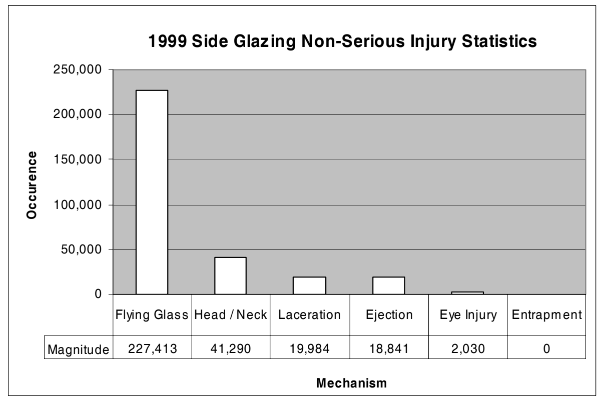

Figure 2: Estimates of side-glazing related non-serious injury occurrence by type.

INJURY MECHANISM ANALYSIS

Injury from glazing contact has long been of concern. Both tempered and laminated glazing designs of today produce fewer injuries than did previous formulations. Fewer vehicles produced today contain laminated side glass than do tempered; it is not possible at this time to conduct a robust statistical analysis of injuries in rollover collisions comparing the two, but current and previous work is sufficient to give a relative injury comparison.

Digges and Eigen [20] showed that in multiple-roll rollovers the rate of injury, even for unrestrained occupants, is less than 5% regardless of the number of rolls, Figure 3. For ¼-roll collisions, approximately 94% of the severely injured occupants received their injuries either from impact with another vehicle or from impacts with fixed objects (e.g., trees, poles) either before or during the rollover. The injury rate for one quarter-turn collision involved vehicles that do not impact other vehicles or fixed objects is less than one per 100 exposed.

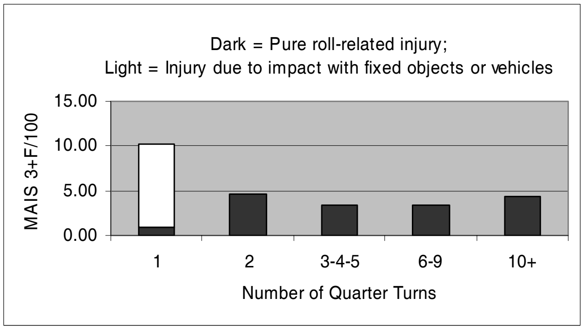

Figure 3: Injury rate of unbelted non-ejected front seat age 12+ occupants with serious injuries in rollovers by number of quarter-turns [20].

Partial and Complete Ejection

The greatest risk of serious occupant glazing-related injury is associated with ejection through the window. Previous work [8;9] has detailed the failure mechanisms of side glazing facilitating ejection. Window size is also important; ejection through glazing from 2-door cars is twice as likely as it is with 4-door vehicles [19]. This is the reason that side window sizes of school buses are restricted. Three-point passive safety belts are principally designed for frontal impact injury mitigation, particularly those with B-pillar mounted D-rings. During the chaotic motion generated by highway speed rollovers, even initially properly-belted occupants can be partially or fully ejected, Figure 4. Seat belts are not a panacea. Digges showed that although a consistent majority of rollover fatalities were determined or believed to have not been wearing their seat belts, a substantial 28% were, in fact, restrained but died anyway [18]. If ejected, the chances of serious injury and fatality increase. Estimates of the increased risk of MAIS 3+ injury due to ejection range up to 40 times as high for ejected vs. non-ejected occupants [36;39].

The study presented in Table I indicates the percentage of serious injuries and fatalities to occupants who remained in their vehicles during light vehicle rollover [16]. The findings indicate that approximately 4% of unbelted occupants incur severe injury or death in rollovers when completely contained. For those occupants who remain belted throughout the rollover accident, the percentage declines to less than 3%.

Figure 4: Sport utility vehicle rollover with sunroof ejection, probable 3 complete rolls [29].

Table 1: Percentage of serious injuries (MAIS 3-5) and fatalities sustained by occupants in light vehicles during rollover [16].

Restraint	No Ejection	Complete Ejection
Unbelted	4.2	34.9
Belted	2.5	40.8

It has long been recognized that tempered side glass is brittle and contains little or no inherent energy-absorbing capability [56]. Once broken at any point, it can no longer offer any occupant containment and in fact becomes more hazardous than a moveable window that has been retracted. As early as 1968, HPR laminated side glazing has been described as "state of the art" for energy absorption and occupant containment [26]. Significantly, the "P" in HPR refers specifically to occupant ejection mitigation, rather than impact protection from outside objects [47]. The change to the HPR windshield in the mid 1960s occurred after the domestic auto industry exchanged laminated side glazing for tempered in the early 1960s, and therefore the entire vehicle did not take advantage of this new technology.

Occupant retention side glazing for passenger vehicles has been effectively demonstrated by Clark and Sursi [13], who used 8 dolly rollover tests to show 100%

effective occupant containment, even for those 6 tests with unbelted first row anthropomorphic test dummies (ATDs). A set of pictograms currently applied to many St. Gobain laminated glass side windows is shown in Figure 5, indicating its energy absorption capability, showing occupant retention at lower left, and intrusion resistance at lower right.

Figure 5: Laminated side glazing pictograms signifying "occupant containment" (left) and "exterior impact resistance" (right).

The proof of the efficacy of laminated glass is shown in the two photographs of Figure 6. The top photo shows an ATD impact into a Volvo S80 right rear door at an initial inclination angle of approximately 17^o at a nominal 16 kph (10 mph). The second photo at bottom shows a laminated S80 front door with two surface chips indicating a foiled entry attempt.

Statistical work by Batzer, et al. [10] indicates that vehicles with commercial first row moveable laminated side glazing that is not optimized for occupant retention still produce fewer occupant ejections than do equivalent vehicles with tempered first row side glazing. Other technologies are available to rollover collision injuries. The most promising seems to be electronic stability control to prevent such accidents and side curtain airbags that are purpose-designed to contain occupants rather than to only provide impact amelioration. Laminated side glass provides a reaction surface for these airbags, increasing their effectiveness.

Figure 6: Volvo S80 glass impact performance - containment (top); security (bottom).

Occupant to Glazing Impact

Historically, the vast majority of neck and head injuries in automobile crashes result from contacts with relatively rigid structures such as the pillars and rails [45]. To address this, the FMVSS 201, *Occupant Protection in Interior Impact*, requires energy absorbing materials on various components. As part of their occupant retention glazing analysis [39;40;42], the National Highway Traffic Safety Administration (NHTSA) conducted a study including the scope of current injury rates, technical feasibility, cost, tradeoffs, and potential benefits and disbenefits, particularly for ejection injuries prevented and possible increased occupant-to-glazing contact injuries. Various side glazing materials were studied including monolithic tempered as the baseline, HPR trilaminate, a non-HPR trilaminate, polycarbonate (monolithic rigid plastic), and glass-plastic bilaminate. NHTSA conducted free-motion headform tests to measure HIC (head injury criterion) indicating potential brain injuries, side impact sled tests to measure potential neck injuries, and virtual rollovers of human models capable of giving injury data.

For a frontal barrier crash at 48 kph (30 mph), the FMVSS 208 [2] sets the maximum permissible HIC (Head Injury Criteria) level at 1000 for 36 ms (HIC 36) as defined by:

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt \right]^{2.5} (t_2 - t_1) \qquad (1)$$

where: a is the resultant head acceleration; t_2-t_1 = 36 ms; and t_2 and t_1 are selected to maximize HIC. It should be noted that, then as now, no injury criteria in side impacts to the head for either HIC or other injury mechanisms are generally agreed upon by NHTSA. During side impacts and rollover collisions, the head and shoulders can hit virtually any portion of the glazing. Two points, the upper rear corner of the glazing and the approximate geometric center were chosen by NHTSA for study, Figure 7:

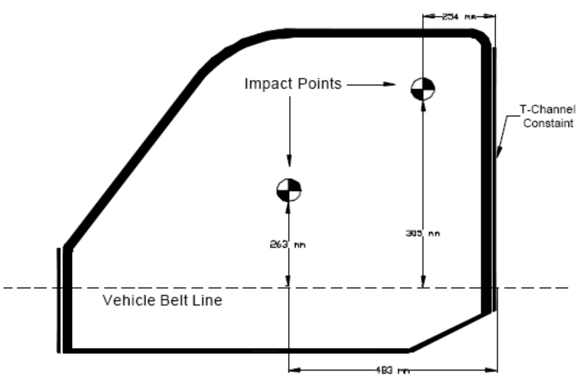

Figure 7: NHTSA targeted glazing impact locations [40].

NHTSA's free motion headform tests indicated that head and brain injury are both unlikely with any side glazing formulation considered. A combination of hits to the geometric center of the glazing and the upper rear corner were used; their averages are shown in Figure 8. Note that for this and the following NHTSA graphs, the number of individual tests per glazing type is included in parenthesis.

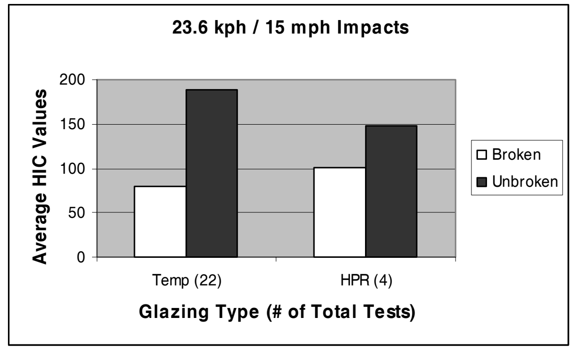

Figure 8: Average of center and corner impact HIC values for 23.6 kph strikes [40].

As expected, unbroken lites produce a greater injury potential than do broken lites that fail to completely retain the headform. The increased rigidity of the tempered lites ensured a higher HIC when unbroken. However, when broken, the HPR lites, with their greater retention capability showed a higher HIC value. None of the testing of tempered or HPR side lites showed values close to 1,000, which is an agreed to threshold for serious injury.

NHTSA also performed HYGE sled tests, moving doors containing experimental lites at speeds of up to 24 kph (15 mph) into the ATDs. To determine the maximum neck injury potential of such impacts, the dummy was tilted to about 26^o toward the glazing to help ensure that initial contact was by the head, rather than the shoulders, maximizing neck loading, rather than realism. In actual rollover collisions, occupant to glass loading is generally substantially less than 24 kph [10], and in side impact collisions the shoulders typically impact the window prior to the head, affording head and neck protection. The rigidity of the Hybrid-III neck ensured the neck orientation remained as desired. The values determined for the tests using the experimental glazing panels are given in the Figures 9-11. Note that there were not, and are not, neck injury criteria for side impacts that are generally accepted by NHTSA researchers. The criteria given by NHTSA in two different 1999 publications [22;40] differ significantly.

Figures 9-11 show five individual data points per set of tests; 2 tempered, 3 HPR. The white portion within the center of the bars shows the minimum, mean, and maximum values of the test. Again, the number of tests performed is shown in parenthesis on the horizontal axis. The dark band which extends past the maximum and minimum values gives a confidence interval of the mean, by assuming that occupant to glazing impacts are Gaussian (normally) distributed.

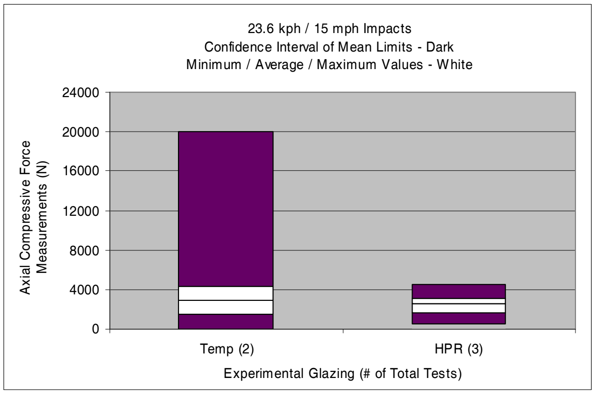

Figure 9: Axial compressive force [40].

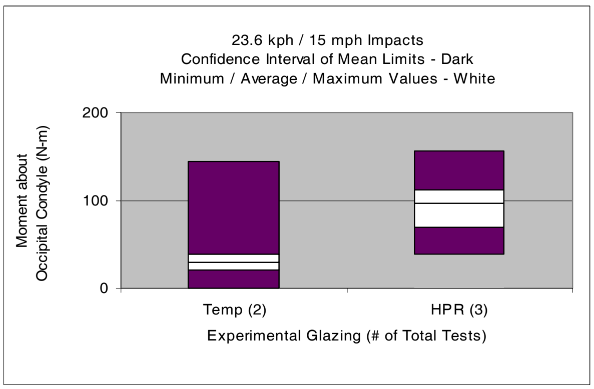

Figure 10: Moment about occipital condyle [40].

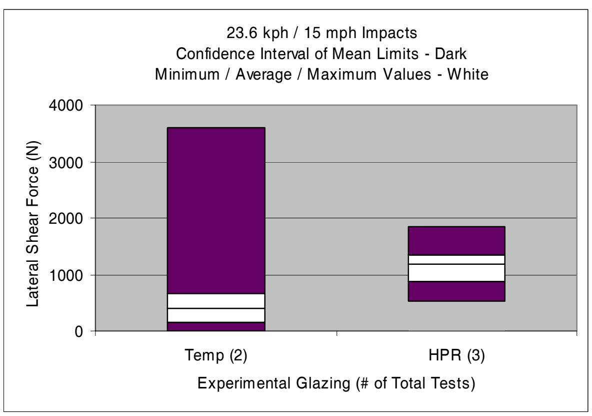

Figure 11: Lateral shear force [40].

As is shown, significant variability was measured in lateral neck shear loads, axial compression, and moments about the occipital condyles. Further, the dearth of measurements (2 tempered tests, 3 HPR laminate tests) ensures that the confidence intervals of the mean are very broad and overlap for the two glazing materials for each injury mechanism. It was observed that occupant to glazing impacts were, in general, more severe with HPR laminated than tempered for the limited data set presented. However, the occupant usually does not strike tempered glass in rollover collisions with sufficient force to cause fracture, as the glazing is already broken out due to body flexure and ground impact forces [16;36].

NHTSA's experimental work demonstrated that currently available HPR glazing used in side positions is capable of retention, has low HIC values and probably does not exhibit a potential for head or neck injury for healthy occupants at likely rollover impact velocities. In fact, NHTSA declared, "…even if there can be small increases in low level neck injury, it is anticipated that the fatality prevention benefit of advanced glazing would likely greatly outweigh any such disbenefits" [40].

NHTSA's work has confirmed previous insights. When tempered glazing was being compared to the old style, non-HPR laminated glazing in the 1960s, the similarity in impact trauma was recognized. Patrick stated in his 1995 SAE paper [46] "Laminated side glass would not be hazardous from an impact standpoint (except for laceration) when struck with the glass in its normal position."

A further comparison can be made with non-HPR to HPR type windshields. The resistance to penetration dramatically increased with this newer technology, and could presumably have caused more blunt impact trauma. According to Kahane [30], "With pre-HPR glazing, there was a 50 percent probability that an unbelted occupant would penetrate the windshield in a frontal crash with a Delta V of 14 miles per hour. With HPR glazing, the likelihood of penetration does not reach 50 percent until the Delta V is 31 mph." The difference between these two velocities for a fixed occupant mass is 120% greater momentum and 390% greater kinetic energy. Kahane continues, "HPR windshields had little or no observed effect on injuries characteristic of blunt impact trauma: concussions, contusions and complaints of pain."

Rushworth, et al. [50], agree with Kahane. They estimated in the late 1960s that tempered windshields outnumbered laminated windshields in Australia by 8:1. Further, these 6 mm (quarter inch) nominal thickness tempered windshields required up to 9,100 N (2,050 lbs) to fracture. Yet, "…no serious closed head injuries from impact with the windscreen alone have been encountered by us…this aspect appears to be unimportant." Sances, et al., showed through drop testing of Hybrid-III dummies that the potential for neck injury due to impact into laminated side glazing is low in rollovers [51;52].

Entrapment

Testing and experience show that neither tempered nor laminated glazing is easy to penetrate without tools. Quasi-static pushout tests of moveable side lites show production tempered glass to take over 500 lbs of force without fracture. While laminated glass can be kicked through with multiple impacts, tempered glass will not progressively damage, and will resist most human attempts at fracture.

The Cornell Aeronautical Laboratory studied regarding automobile glazing as an injury factor in accidents [12]. They indicated that entrapment was extremely rare, and requires all of the following conditions to be true (emphasis in original text):

- "All car doors jammed shut or otherwise blocked, <u>and</u>
- "All windows rolled up, <u>and</u>
- "All windows jammed such that they could not be rolled down, <u>and</u>
- "All glass surfaces intact."

Additionally, the occupant(s) must have survived the initial accident to make egress relevant. The researchers studied 30,000 accidents, of which only 755 cases presented a situation in which escape through the doors was not possible. "In only 12 of these was there a need for immediate escape because of fire or immersion. In none of the 12 was there a clear-cut indication that egress depended upon the necessity for breaking a glass surface. Three hundred of the 755 were studied individually and the indications were that egress would have been possible without resorting to breaking glass in most, and perhaps all, cases…it stated with confidence that the number is extremely small."

The findings of the Cornell report were supported by the *Submerged Vehicle Safety* study [31]. This report listed as its purpose, "to determine the sequence of events when automobile is suddenly submerged in water deeper than the vehicle itself, what passengers can do to save themselves, and how passengers can be rescued". Four passenger cars were used for data acquisition and three others were used for test feasibility studies. A total of forty-nine tests were run using a 4 meter deep pool. The recommendations regarding proper actions required 20 pages of text and a 20-minute film in explanation. Escape recommendations included:

> "Following impact, for a vehicle entering on its top, the occupant can escape by keeping his head against the floorboard, inhaling deeply, and leaving the vehicle through the open windows which are under the surface.
>
> "If the occupant is unable to escape through the front windows after impact, he should position himself to the rear of the passenger compartment in the existing air so as to provide more time to plan his escape, as the vehicle will descend to the bottom on its top, engine first. Escape at this time can be accomplished through an open window, or by opening a door."

According to Morris, et al. [38], "whether using laminated side and rear glass would in fact make it difficult for an entrapped occupant to escape can only be speculated at this stage since field data is not available to allow conclusions to be drawn." They conclude, "In summary, we have shown that ejection is an undesirable outcome and that retention is more desirable. Introduction of any alternative security glazing material in the side and rear windows would be welcome, especially as it is anticipated that it would reduce the incidence of ejection."

Patrick's analysis of available glazing materials [46] affirmed that laminated glass gives a slight performance edge over tempered in entrapment situations. However, he felt that this was not even of concern in Holland, which has a high number of canals along the roadways. Hassan, et al. [25] studied the implications of laminated side glazing for occupant safety, and determined that "occupant entrapment is not likely to be a major problem."

Laceration

The dominant glazing injury mechanism, by far, is that of laceration [46;57]. By studying the leading automobile accident mode, the frontal collision (representing ~60% of all accidents for passenger vehicles and light trucks [44]), it is possible to gain insight into the lacerative potential of windshields, and by extension, tempered and laminated side glazing. The contact mechanics are comparable, and in Europe, tempered windshields were produced side-by-side with HPR-formulated windshields for years. Field experience has led Western Europe to follow the United States in requiring HPR laminated glazing for all windshields of passenger vehicles.

Patrick, et al. [48], wrote that, "Severe lacerations resulted in all impacts in which tempered glass broke. Less severe lacerations were found for the laminated windshield impacts at comparable speeds." They go on to indicate that the consensus of German researchers in the 1960s was that penetration of tempered windshields caused severe facial lacerations and eye injuries ranging from minor to total loss of sight. They recommended the usage of laminated over tempered windshields due to the disproportionate number of injuries, particularly laceration, caused by tempered glass.

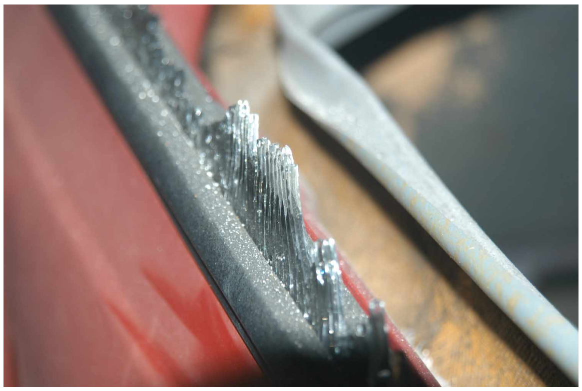

Figure 12: Laceration source from tempered glass fragments, fractured fixed quarter lite.

The superiority of HPR windshield glass over the previous formulation is universally recognized, "HPR windshields have already been informally evaluated. The dramatic reduction in the demand for facial plastic surgery following the introduction of HPR made it clear to the safety community that [the requirement for] HPR has been, perhaps, more successful than any other standard [30]." The slicing and soft tissue laceration commonly seen in pre-HPR glazing was replaced by "relatively minor scrape-like abrasions," some pitting injuries, and fewer concussive brain injuries [27;55].

In multiple-roll rollovers, the possibility exists for multiple impacts against laminated occupant-retention glazing. Batzer, et al. [7], found that the laceration potential did not substantially increase in multiple impacts against EPG style laminated side glass with multiple impacts without through-glass penetration, Figure 13.

The lacerative potential of tempered glass fragments depends upon how it is handled. Casual, low-pressure handling of "dice like" fragments of tempered glass gives an unrealistic impression of their danger. Such fragments contain points and edges which are sharp, not rounded as is sometimes claimed.

Figure 13: Blunt impactor testing of EPG style laminated side glazing.

Severy and Snowden [54] conducted glazing tests and reported that, "Subsequent examination of high speed movies of these experiments revealed that tempered glass fragments may move as clusters, an inch or two across the long axis, so that the comment concerning hazard arising from tempered glass weight should be modified. It was also observed in collecting the fragments that while many particles are cube-like, as described by other investigators, most were by no means free of sharp points or edges, making them very difficult to handle without cutting one's hands." Yudenfriend and Clark [57] found in door impact testing that 20-40% of the glass fragments flew inward toward the occupant survival space, and that they entered that space at velocities as high as 23 km/hr (14 mph). The speed, size, shape, and sharpness of tempered glass fragments explain why some shards have been found to penetrate skin and skull and even enter the brain [57]. Citations regarding skull penetration of glazing fragments refer exclusively to tempered fragments, rather than to the annealed fragments produced by laminated glass [50;24].

Ocular Injuries

When tempered glass shatters in collisions, it is usually stressed under the conditions of bending or shock loading, and can shower fragments into the occupant space. Laminated glazing spalls and creates small, even dust-like, fragments. However, the quantity of laminated glass fragments detaching from the polymer laminate is, in general, less than 1% of that from tempered glazing. In one side collision with fractured tempered glazing, a woman complained to her physician of persistent eye irritation. This lead to an X-ray examination that indicated that a fragment was lodged behind the eyeball itself and rested against the optic nerve. This can be explained by gross inertial deformation of the eye during the crash pulse that caused a separation between the ball and the surrounding tissue, allowing introduction of the fragment.

HPR laminated versus tempered windshield ocular injury was investigated by Langwieder [32], who found only one eye injury from HPR laminated glass from those 228 occupants who had head injuries. Tempered windshields induced about 17 cases of eye injury from 545 head injuries. This represents a sevenfold increase in injury rate for tempered windshields over laminated.

Figure 14 Fractured tempered back lite after rear impact. Driver penetrated window and was blinded in left eye.

Both McLean and Mackay, et al., discussed the severe injuries that occur from the tempered fragments that remain at the frame around the windshield opening [37;35]. The ANSI Z26.1 standard does not regulate the size or shape of fragments at the periphery of the window.

The higher injury rate associated with tempered windscreens when compared to HPR laminated windshields was also investigated by Mackay [34]. He concluded that, "Eye injury from toughened glass windscreens is a substantial problem reflected in the clinical literature from at least 12 countries. By contrast, countries which use HPR laminated glass report no incidence of eye injuries from the windscreen of any consequence."

Huelke studied a 27-month period of National Crash Severity Study data (January 1977-March 1979) comprising 106,000 passenger vehicles involved in towaway crashes [28]. The data included vehicles with pre-HPR windshields. No single occupant of the 106,000 accidents studied had been totally blinded, but there were 29 occupants who received serious ocular injuries. Various objects within and outside of the vehicle caused the various eye injuries, but the predominant agents (~64%) were the windshield and side glazing.

The mechanism of increased laceration and ocular injuries produced by tempered over laminated HPR glazing is illustrated in the photographs given in the Figure 15. Note that these vehicles are not equipped with first row airbags. The vehicles were directed into a frontal impact with a fixed barrier at 12 o'clock. The unrestrained right-side dummies moved forward and impacted the dashboard with their knees and chests, and against the windshields with their heads.

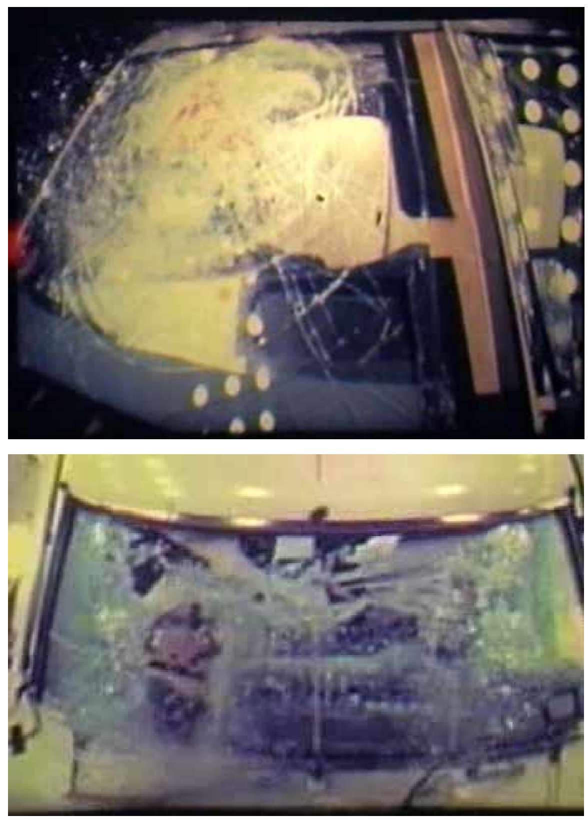

Figure 15: Passenger (right) side dummy impact against an HPR laminated windshield (top) and a tempered windshield (bottom) [23].

The impact against the HPR laminated windshield (top) shows typical performance. The glass fractures but largely remains adhered to the polymer interlayer. Spalled fragments are shown from the exterior glass ply against the dark background. The dummy's head does not show significant relative downward motion (scrub) against the inboard glass ply that would have presented an enhanced laceration hazard. The impact against the tempered windshield produces progressive fracture of the glass, with maximized laceration. That is, the glass does not break and fly away in a single instant. It largely retained its planar shape and presented progressively formed edges against the dummy's face as the head moved forward and downward toward the dashboard.

In 1975, UK researcher G. Murray Mackay wrote, "It is of note that all papers reporting eye injuries originate from countries where the windscreens of cars are made from toughened glass [33]."

ANALYSIS AND CONCLUSIONS

The injury mechanisms of both laminated and tempered automotive side glazing constructions have been compared. This study confirms and supports with new research the body of 30 years of work in a comprehensive manner. The mechanisms of injury for automotive side glazing are identical to that of the windshield, of which has been written, "The principal finding of this field study of accidents is that tempered glass is inferior, from the viewpoint of producing injury, than the 0.030" interlayer laminated glass" [35].

The greatest serious injury threat to both belted and unbelted occupants is that of complete or partial ejection. If the side window portal is kept covered in a collision, occupant containment can be realized. The greatest non-serious injury mechanism is that of laceration, principally through flying fractured tempered safety glass. Ocular injuries are shown to be relatively rare, and other injuries, such as entrapment-induced injury, are even rarer. The safety benefits of the major two types of side glazing are listed in Table 2 below.

Table 2: Side glazing injury attributes
most beneficial glazing marked "X"

Attribute	Tempered	Laminated
Airbag Assistance		X
Containment		X
Entrapment		X
Eye Injury		X
Fire Protection [53]		X
Impact Blunt Trauma	Neither	
Laceration		X
Skull Penetration		X

Significantly, LSG has been shown to be the superior material for addressing the two injury causation mechanisms (impact and ejection) given as purposes for the FMVSS 205. For the third purpose, providing driver visibility, LSG is also superior, as it does not vacate the portal when fractured or pixelize. Thus, for each of the three stated FMVSS205 purposes, laminated safety glazing has been shown to be the superior material for side window applications when compared to tempered safety glazing.

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REFERENCES

[1] 49 CFR Ch. V, 571.205 Standard 205, Glazing Materials, 2001.

[2] 49 CFR Ch. V, 571.208 Standard 208, Occupant Crash Protection, 2001.

[3] Alexander, H. M., P. T. Mattimoe, and J. J. Hofmann, 1970. "An Improved Windshield," SAE Mid-Year Meeting.

[4] American Standard Safety Code Z26.1-1938.

[5] ANSI/SAE Z26.1-1996. American National Standard for Safety Glazing Materials for Glazing Motor Vehicles and Motor Vehicle Equipment Operation on Land Highways-Safety Standard.

[6] ASTM C1048-04, 2005. "Standard Specification for Heat-Treated Flat Glass—Kind HS, Kind FT Coated and Uncoated Glass."

[7] Batzer, S. A., J. L. Evans, K. A. Allen, M. R. Martin, and D. R. Phillips, 2005. "Biomechanical Analysis of Headform Impacts into Automobile Side Glazing," ASME 2005 Summer Bioengineering Conference, Vail Cascade Resort & Spa, Vail, CO.

[8] Batzer, S. A., 2005. "Performance of Automotive Side Glazing In Rollover Collisions," Materials Science & Technology 2005 Conference and Exhibition, Failure Analysis Symposium Proceedings, Pittsburgh, PA.

[9] Batzer, S. A., 2006. "Failure Mechanisms of Automotive Side Glazing in Rollover Collisions," Journal of Failure Analysis and Prevention, Vol. 6, No. 3, pp. 6-11, 33-34.

[10] Batzer, S. A., G. G. Herndon, C. K. Thorbole, H. Chamberlain, D. R. Phillips, and H. Yudenfriend, 2007. "Automotive Side Glazing for Primary and Secondary Occupant Retention," SAE 2007-01-1546.

[11] Batzer, S. A., April, 2007. “Automotive Side Glass Related Injuries in Rollover Collisions,” Professional Safety, Journal of the American Society of Safety Engineers.

[12] Campbell, B. J., and T. Bopens, 1964. “Automobile Glazing as an Injury Factor in Accidents,” Cornell Aeronautical Laboratory, CAR Report No. VJ-1825-R-1.

[13] Clark, C. C., and P. Sursi, 1989. "Rollover Crash and Laboratory Tests of Ejection Reduction by Glass-Plastic Side Windows and Windshields," SAE Technical Paper 890218.

[14] Clark, C. C., H. Yudenfriend, and A. S. Redner, 2000. "Laceration and Ejection Dangers of Automotive Glass, and the Weak Standards Involved. The Strain Fracture Test," 44th Annual Proceedings, Association for the Advancement of Automotive Medicine, Chicago, IL.

[15] Cohen D., K. Digges, and H. Nichols, 1989. “Rollover Crashworthiness Classification and Severity Indices,” Proceedings, 12th International Technical Conference on Experimental Safety Vehicles.

[16] Data Link Inc, 1993. “Injuring Contacts in Light Vehicle Rollovers,” Washington, DC. Prepared for the National Highway Traffic Safety Administration Crashworthiness Staffs.

[17] Department of Transportation, 2006. National Automotive Sampling System, http://www.nrd.nhtsa.dot.gov/departments/nrd-30/ncsa/NASS.html, 1999 statistics.

[18] Deutermann, W., 2002. “Characteristics of Fatal Roll Crashes,” DOT HS 809, 27.

[19] Digges, K. 2002. “Summary Report of Rollover Crashes.”

[20] Digges, K., and A. M. Eigen, 2003. “Crash Attributes that Influence the Severity of Rollover Crashes,” Proceedings of the ESV Conference, paper 231.

[21] Enhanced Protective Glass Automotive Association, http://www.epg.com/, 2006.

[22] Eppinger, R., et al., 1999. “Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems – II,” National Highway Traffic Safety Administration.

[23] Ford Motor Company, 1976. “Impact Performance Characteristics of Laminated & Tempered Windshields,” (video).

[24] Greene, J. E., Calspan Field Service, Inc., 1976. “Occupant Survivability in Lateral Collisions: Summary Report.”

[25] Hassan, A. M., M. Mackay, J-Y. Foret-Bruno, J-F. Huere, and K. Langwieder, 2001. “Laminated Side Glazing Implications for Vehicle Occupant Safety,” IRCOBI Conference, Isle of Man (UK), 283-294.

[26] Hill, G. P., 1969. “Occupant Protection…review of energy absorbing devices,” SAE National Convention.

[27] Huelke, D. F., and W. A. Chewning, 1968. “Crash Performances of the New Automobile Safety Features,” Pre-Crash Factors in Traffic Safety, 12th Annual Symposium, The American Association for Automotive Medicine.

[28] Huelke, D. F., J. O’Day, and W. H. Barhydt, 1982. “Ocular Injuries in Automobile Crashes,” The Journal of Trauma, Vol. 22, No. 1, pp. 50-52.

[29] Indiana Officer’s Standard Crash Report, 12/20/2001. Case 200118043, Investigating Officer Deputy Larry Allen.

[30] Kahane, C. J., 1985. NHTSA Report Number DOT HS 806 693, “An Evaluation of Windshield Glazing and Installation Methods for Passenger Cars.”

[31] Kuhn, B. J., 1962. “Submerged Vehicle Safety,” 1962 Safety Congress, Chicago, Illinois, National Safety Council.

[32] Langwieder, K., 1972. “Interior Safety of Automobiles,” Proceedings, Third International Technology Conference on Experimental Safety Vehicles, 2-217-220.

[33] Mackay, G. M., 1975. “Incidence of Trauma to the Eyes of Car Occupants,” Trans. Ophthal. Soc. U.K., 95, 311.

[34] Mackay G. M., 1978. “Injuries from Windscreens – A Review of Some Recent Literature,” University of Birmingham Department of Transportation and Environmental Planning, Departmental Publication Number 53.

[35] Mackay, G. M., A. W. Siegel, P. V. Hight, 1970. “Tempered versus HPR Laminated Windshields: A Comparative Study of United Kingdom and United States Collisions,” 14th Stapp Car Crash Conference.

[36] Malliaris, A. C., J. H. DeBlois, and K. H. Digges, 1996. “Light Vehicle Occupant Ejections – A Comprehensive Investigation,” Accident Analysis and Prevention.

[37] McLean, A. J., 1969. "Performance of Automotive Glazing in Urban Accidents," 13th Stapp Car Crash Conference.

[38] Morris, A. P., A. M. Hassan, G. M. Mackay, and S. Parkin, 1993. "A Case for Security Glazing," 37th Annual Proceedings, AAMA, San Antonio, TX.

[39] NHTSA Advanced Glazing Research Team, 1995. "Ejection Mitigation Using Advanced Glazing: A Status Report."

[40] NHTSA Advanced Glazing Research Team, 1999. "Ejection Mitigation Using Advanced Glazing: Status Report II."

[41] NHTSA, 2000. "1999 Traffic Safety Facts."

[42] NHTSA Advanced Glazing Research Team, 2001. "Ejection Mitigation Using Advanced Glazing: Final Report."

[43] NHTSA, 2003. "Initiatives to Address the Mitigation of Vehicle Rollover."

[44] NHTSA, 2004. "2002 Traffic Safety Facts."

[45] Ommaya, A. K., S. Backaitis, W. Fan, and S. Partyka, 1983. "Automotive Neck Injuries," 9th International Technical Conference on Experimental Safety Vehicles, 1982. Also as NHTSA Report DOT HS 806 341, 274-278.

[46] Patrick, L. M., 1995. "Glazing for Motor Vehicles – 1995," SAE Technical Paper 952717.

[47] Patrick, L. M., and R. P. Daniel, 1964. "Comparison of Standard and Experimental Windshields," 8th Stapp Car Crash Conference.

[48] Patrick, L. M., K. R. Trosien, and F. T. DuPont, 1970. "Safety Performance Comparison of 30 MIL HPR Laminated and Monolithic Differentially Tempered Windshields," SAE Paper 700427.

[49] Rieser, R. G., and G. E. Michaels, 1965. "Factors in the Development and Evaluation of Safer Glazing," 9th Stapp Car Crash Conference.

[50] Rushworth, R. G., and J. G. Toakley, 1969. "Windscreen Injuries of the Brain," The Medical Journal of Australia, p. 80-83.

[51] Sances, A., F. H. Carlin, and S. Kumaresan, 2002. "Biomedical Engineering Analysis of Glass Impact Injuries," Critical Reviews in Biomedical Engineering, 30 (4-6).

[52] Sances, A. Jr., S. Kumaresan, F. Carlin, K. Friedman, and S. Meyer, 2003. "Biomechanics of Occupant Ejection During Rollover Accidents," Southern Biomedical Engineering Conference and Symposium on Aortic Valve Sparing Surgery.

[53] Severy D., D. M. Blaisdell, and J. F. Kerkhoff, 1974. "Automotive Collision Fires," Proceedings of the Eighteenth Stapp Car Crash Conference, 113-200.

[54] Severy D., and W. Snowden, 1962. "A Review of the State of Knowledge and Research Concerning Laminated and Tempered Glass in Motor Vehicles," prepared for the Assembly Interim Committee on Transportation and Commerce, University of California Los Angeles, Institute for Transportation and Traffic Engineering, Transportation Research Information Service Accession Number 690524.

[55] Widman, J. C., 1965. "Recent Developments in Penetration Resistance of Windshield Glass," SAE Paper 654074.

[56] Yudenfriend, H., 1961. "The Issue and the Challenge," Glass Digest.

[57] Yudenfriend, H., and C. C. Clark, 1997. "Glazing Effects of Door or Frame Deformations in Crashes, Part 2" SAE Technical Paper 970121.